Ink-Jet Printing

Minute drops of ink, squirted from a nozzle and steered in flight, can be made to form printed characters. The ink-jet technology is particularly well suited to printing at the command of a computer

by Larry Kuhn and Robert A. Myers

The invention of movable type more than 500 years ago transformed the art of printing by decomposing the written word into its basic elements: the letters of the alphabet. Several new printing technologies have taken a further step in the same direction: they break down each character into an array of dots. Both innovations bring the advantage of increased versatility. With movable type the same set of characters can be reassembled over and over to form new texts; with dot-matrix printing the size and form of the characters themselves can be changed at will.

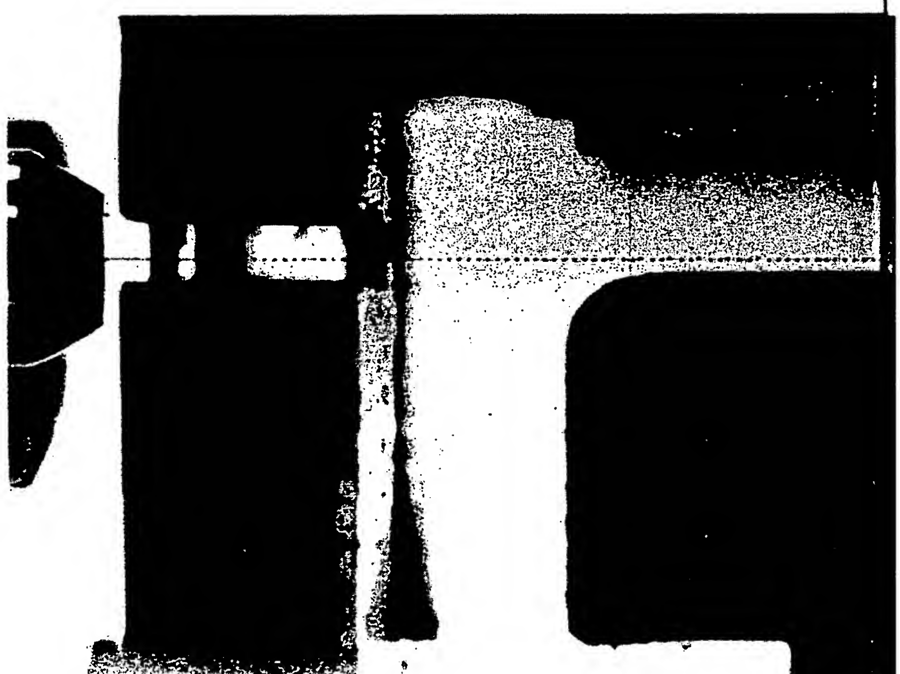
Ink-jet printing is one of the new dot-matrix technologies. Whereas most traditional printing devices work by pressing an inked image of the letter against the paper, the ink-jet printer "paints" each character. A stream of ink issuing from a microscopic nozzle is broken up into small drops that are then directed to specified positions on the paper. The only preexisting image of the character is an electronic one, which is employed to control the drop trajectories.

In principle one might construct an ink-jet press, where many thousands of independently controlled jets would print a magazine or newspaper directly from an electronic representation of the text and illustrations. For now, however, the technology is confined to printing on a more modest scale. The ink-jet printer serves as an output device for a computer or a word-processing system. It is in applications of this kind that versatility is most important. Thousands of identical copies of a single text are seldom needed; instead the machine is called on to make one copy or a few copies of many different documents.

Most computer-output printing is done by machines that have a strong functional resemblance to the ordinary typewriter. They are called impact printers, and they all share the same fundamental mechanism: a preformed image of a letter is made to strike the paper, usually through an inked ribbon. The letters can be mounted on individual type bars, as in the conventional typewriter, or they can be arranged on a disk, on the surface of a ball or on a belt. Most machines print a single character at a time at rates of from 15 to about 50 characters per second. Faster machines print a full line at a time and can produce as many as 50 lines per second.

The dot-matrix printer employs a significantly different mechanism. In an electromechanical version of the matrix printer seven or eight closely spaced wires of tungsten carbide are arranged in a vertical line. Each wire is coupled to a solenoid magnet that can drive the tip of the wire into an inked ribbon and the paper. In operation the line of wires is swept across the page as various combinations of solenoids are energized, forming letters, other characters and the spaces between them.

In an ink-jet printer the dots that compose the matrix are marks left by individual drops of ink. Because the drops are generally much smaller than the wires of an impact matrix printer the resolution of the printed image can be much higher. In the commonest kind of impact matrix printer each character is formed by selecting some of the 35 dots in a five-by-seven array, with the result that many familiar letter forms can only be approximated. Because the wires cannot ordinarily be packed any closer than three or four per millimeter the individual dots remain distinct. The drops generated by an ink-jet printer are small enough and can be placed accurately



DROPS IN FLIGHT were photographed as they moved through the deflection apparatus of an ink-jet printer. The ink emerges from the nozzle at the far left as a continuous jet, which quickly breaks up into drops with a diameter of about 60 micrometers. At the point where the jet breaks up, selected drops are given an electrostatic charge by the electrode immediately to the right of the nozzle. The large metallic structures in the center of the photograph are deflection plates to which a potential of some 3,000 volts is applied. In the electric field between these plates the drops that have acquired a charge are deflected upward by an amount propor-

enough to yield a resolution equivalent to a matrix of 1,000 dots per character. They can be spaced as closely as 10 per millimeter and they overlap slightly, so that no white space is left between the dots. The quality of the resulting printed image is comparable to that produced by a typewriter with a fabric ribbon.

Another potential advantage of ink-jet printing is its quietness. Noise was not an important consideration when a computer and its peripheral devices were large enough to require a room of their own, but today a computer is often installed in an ordinary office, where the noise of most impact printers can be disruptive. The ink-jet mechanism is virtually silent. Because it is mainly an electronic device it also promises greater reliability than the electromechanical components of an impact printer. It should be pointed out, however, that much of the noise and many of the mechanical failures in a printer can be attributed to the machinery that transports the paper, and that machinery is essentially unchanged by the adoption of ink-jet technology.

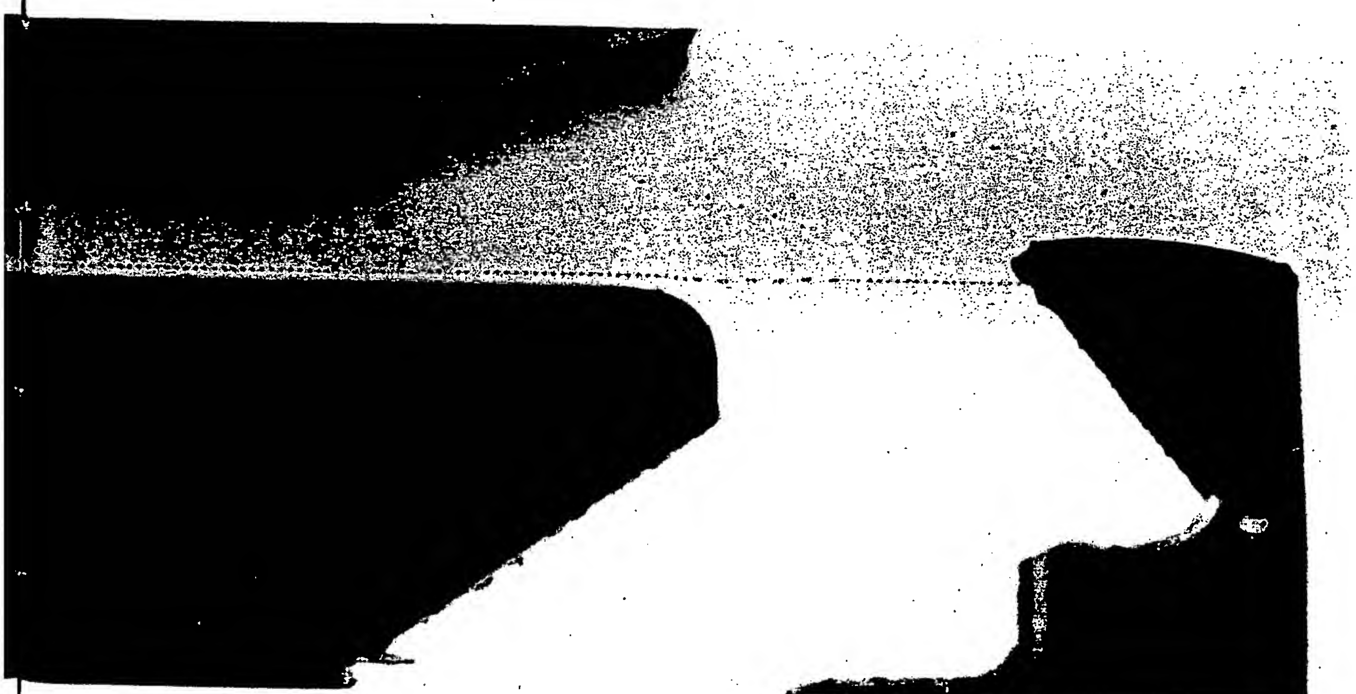
Perhaps the most impressive advantage of the ink-jet printer is its ability to change almost instantaneously the size or style of the type being printed. It would be no more difficult to print Greek or Arabic characters than it is to print the Roman alphabet, and even nonalphabetic languages such as Chinese can be reproduced. Indeed, there are almost no limitations on the form of the material to be printed. Any given point can be either marked with a drop or left blank; to borrow a term from another realm of computer science, the printer is capable of "addressing" all points on the page.

Several methods of ink-jet printing have been devised, of which we shall discuss three. In the first method a single stream of drops is steered electrostatically and in the second the steering is electromagnetic. The third scheme employs multiple ink jets, which are independently directed onto the paper or into a gutter where the unused ink is collected. All three of these technologies rely on a continuous, synchronized stream of drops. There are other methods of ink-jet printing in which the drops are issued on demand, but we shall not discuss them here.

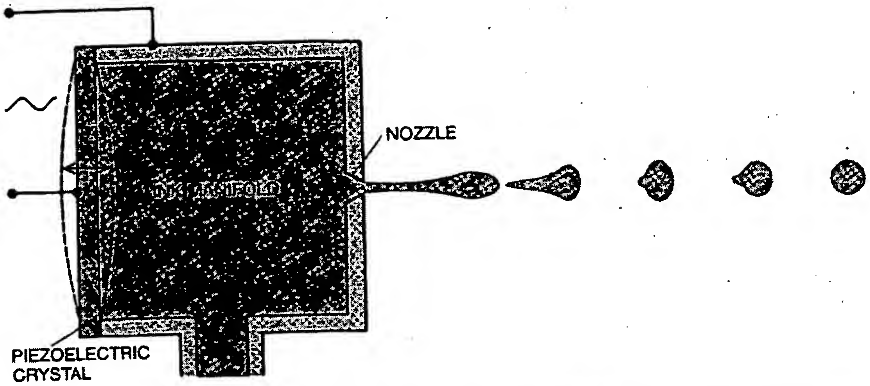
Most of the physical principles underlying the operation of an ink-jet printer were understood in the 19th century. It was not until the early 1960's, however, that the ingenious idea essential to the construction of a practical printer was demonstrated by Richard G. Sweet of Stanford University. In an extended series of experiments Sweet showed that an electric charge could be impressed on the drops that form out of a continuous stream of fluid. What is more, he found that even when the drops were generated at the rate of 100,000 per second, the charge on each drop could be determined independently. The trajectory followed by each drop could then be controlled by passing all the drops through a uniform electric field.

Sweet's immediate aim in these experiments was the construction of a high-speed oscillograph, an instrument for recording rapidly changing electrical signals. The technique has since found other applications, including some that are rather far afield, such as the sorting of cells in blood specimens. The printing of alphabetic characters is one of the more obvious applications, which Sweet himself was among the first to investigate. One way to build a printer, for example, is to mount the drop generator and the various electrodes for charging and deflecting the drops on a movable carriage: the print head. The deflection field then steers the drops to various positions along a vertical line while the entire print head is swept across the page horizontally. If the drops are formed at a rate of 100,000 per second and a typical character is made up of roughly 100 drops, then the maximum printing rate should be about 1,000 characters per second. Actual rates are much slower, however, because not every drop can be utilized; indeed, in a practical printer only about 2 percent of the drops reach the paper.

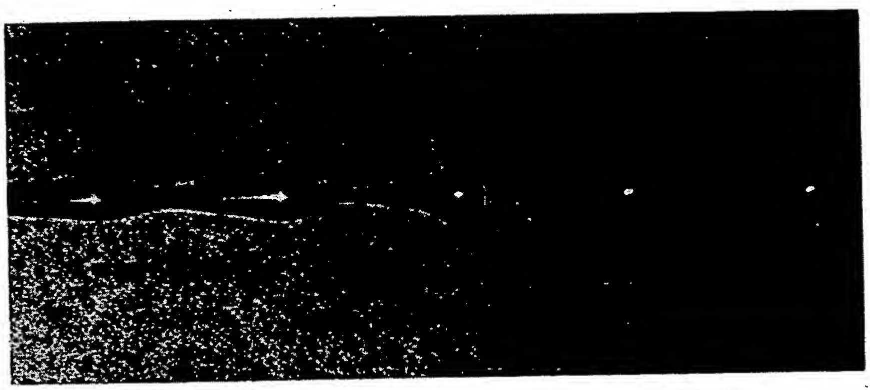
A printer of this kind was first offered commercially by the A. B. Dick Company. The International Business Machines Corporation has since introduced



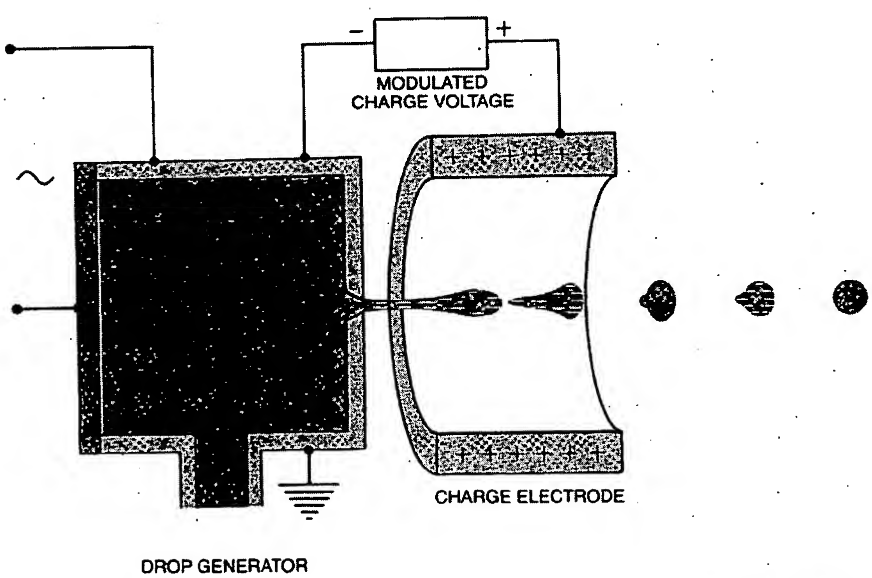
tional to their charge. The uncharged drops continue undeflected to a gutter at the right, where unused ink is collected for recirculation. Only the deflected drops reach the paper, which in an operating printer would be positioned to the right of the gutter and at right angles to the plane of the image. The drops are emitted at a rate of 117,000 per second and move with a speed of about 18 meters per second. Deflected drops fall behind their original positions in the sequence because of aerodynamic drag. Although the photograph appears to show a single set of drops, it actually superposes the images of several hundred sets illuminated at the same positions in their trajectories by successive flashes of a stroboscope. The photograph was made by Carl E. Lindberg of the Office Products Division of the International Business Machines Corporation in Lexington, Ky. It shows components of the IBM 6640 printer mounted on a laboratory test bench.



DROP GENERATOR emits a continuous jet of ink whose breakup into drops is synchronized by an external signal. The ink is forced through a nozzle some 20 to 40 micrometers in diameter under a pressure equal to a few times atmospheric pressure. Ordinarily such a jet would disintegrate into a random spray, but the synchronizing signal creates drops that are uniform in size, velocity and spacing. The synchronization is most commonly brought about by a periodic pressure variation applied by a piezoelectric crystal mounted on one wall of the ink manifold.



FORMATION OF DROPS is governed by surface tension, which amplifies the slight undulation in the surface of the jet created by the synchronizing signal. In the regions where the jet is narrowest the forces resulting from surface tension are greatest, and so they further reduce the diameter until the stream breaks apart into separate drops. The photomicrograph was made by Jean-Claude Chastang of the IBM Manufacturing Research Laboratories at Yorktown Heights, N.Y. Small drops between the major ones are "satellites" that must be suppressed.



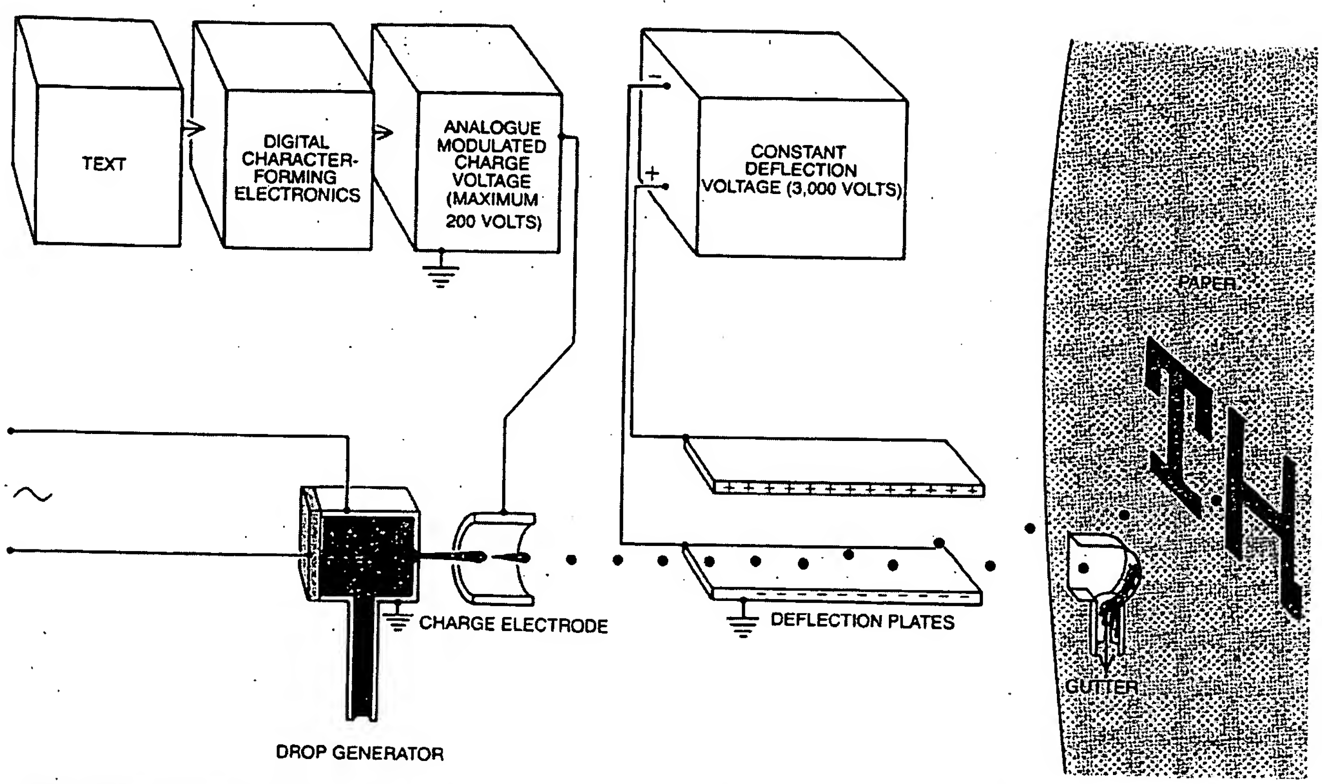
ELECTRIC CHARGE acquired by each drop in a stream can be controlled independently. A positive potential applied to the charge electrode draws electrons (*denoted by minus signs*) through the ink to the tip of the jet. When a drop breaks off, a charge proportional to the voltage on the electrode is trapped on the drop. Charges of nearby drops, however, can alter the charge of a drop that is forming, and voltage must be adjusted to compensate for these effects.

a printer that employs the same means of drop steering to achieve a character image of typewriter quality. Because we are most familiar with the development of the IBM printer, which is now designated the 6640, we shall refer to it as an example in much of the discussion that follows.

The first requirement of an ink-jet printer is a well-defined stream of drops. The interval between drops must be uniform, the drops must all be the same size and they must all be moving in the same direction at the same speed. Almost any jet of liquid, such as the water from a garden hose, will spontaneously break up into drops, but ordinarily the drops are random in size and spacing. For reliable printing the stream must be synchronized, but that is not difficult to achieve. All that is necessary is to impress a periodic rippling on the surface of the emerging jet; the drops then appear at the ripple frequency.

In the IBM 6640 the ink jet is created by forcing ink under moderate pressure (a few times atmospheric pressure) through an opening about 35 micrometers in diameter. It was found convenient to apply the synchronization signal as a small pressure variation. One wall of the manifold that confines the pressurized ink is coupled to a piezoelectric crystal; when an electrical signal of the selected frequency is applied to the crystal, it vibrates rather like a drumhead. The synchronizing frequency is roughly 117,000 cycles per second. The jet emerges from the nozzle at a speed of 17.5 meters per second, and so the interval between drops is about 150 micrometers.

It is not immediately obvious why a stream of liquid should break up into drops at all. The explanation lies in the concept of surface tension, which forces any free liquid to assume the shape of minimum surface area. Simple calculations show that a cylinder of fluid with a fixed volume can reduce its surface area by forming drops if the interval between drops is greater than the circumference of the cylinder. If the surface of the jet is slightly rippled, the force that arises from surface tension is greatest in regions of high curvature. As a result regions that are slightly swelled tend to swell further and regions that are constricted tend to become narrower, forming a neck that finally breaks off. In effect the fluid jet is an amplifier of very high gain that greatly magnifies any perturbation impressed on the stream. In an unsynchronized jet, random drops result from the amplification of random vibrations and variations in fluid flow. Because the amplifying mechanism has high gain the stream can be synchronized by a signal of very small amplitude, one that yields a surface perturbation of a few tenths of a micrometer.



ELECTROSTATIC PRINT HEAD steers each drop to a position on the paper determined by the charge on the drop. The text to be printed is stored in electronic form and is ultimately converted into a sequence of voltages that are applied to the charge electrode. Hence each drop in the stream is given a charge corresponding to one of these voltages. After leaving the drop generator and the charge electrode the drops pass between deflection plates that bear a steady high voltage. In the electric field between the plates a drop is deflected by an amount proportional to its charge. In this way a drop can be directed to any position along a vertical line segment whose length is equal to the height of a character. Movement in the horizontal dimension is provided by transporting the entire print head across the page.

The behavior of fluid jets was studied by a number of 19th-century investigators, and the subject was given a particularly elegant analysis by Lord Rayleigh. The 19th-century theorists were unable, however, to analyze certain subtle effects that cannot be ignored in the design of a printer. In particular, nonlinearities in the amplification process distort the surface of the jet and give rise to much smaller droplets, called satellites, between the desired drops. Because satellite droplets can contaminate the print head or cause misplaced marks on the paper they must be suppressed. In the past few years several attempts to explain satellite formation theoretically have been undertaken but without complete success. Hence the design of a drop generator is carried out mainly by cut-and-try methods.

Electric charge is applied to the drops by a small electrode that surrounds the region where the drops break off from the jet. A voltage is applied between this charge electrode and the drop generator. If the voltage is positive, electrons are drawn to the tip of the ink stream by electrostatic attraction, and when a drop breaks free, it carries some of these electrons with it. Once the drop has separated from the jet it is electrically isolated and the charge cannot leak away, even when the voltage on the charging electrode changes. The charge on a drop is proportional to the voltage on the charge electrode. That voltage is limited to a few hundred volts; if it were much greater, repulsion between adjacent charged drops would become unmanageable. Furthermore, as the voltage increases, repulsion between charges within a drop eventually exceeds the surface tension of the liquid and the drop explodes.

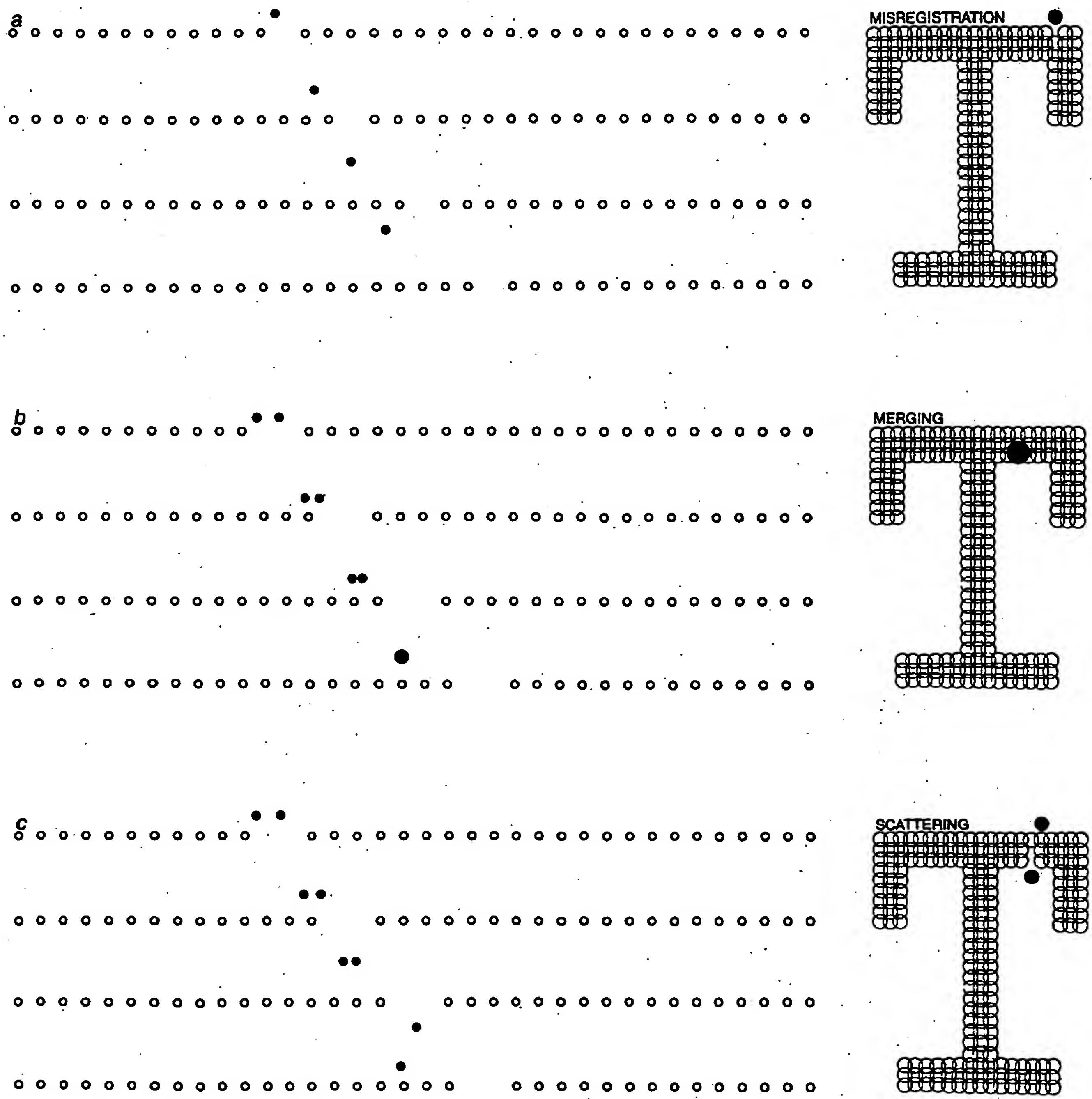
After leaving the charge electrode the drops pass into the electric field of the deflection plates. The magnitude of the field is determined by the distance between the plates and by the voltage applied to them; an upper limit is the field strength at which there is arcing between the plates. In principle drops could be given either positive or negative charges, so that they would be deflected either up or down by the fixed voltage on the deflection plates. In practice it is simpler to design drive circuits that give all the drops a charge of the same polarity so that they are all deflected in the same direction. Here we shall assume that all drops have a negative charge (or zero charge) and that the deflection plates are arranged in such a way that all charged drops are deflected upward.

Character generation begins with an electronic specification of the positions on the paper to be marked by drops. The specification can be stored in a semiconductor memory device such as a read-only memory and called up on demand. The pattern of binary numbers in the memory is then decoded and employed to specify the sequence of voltages applied to the charge electrode. If the print head moves across the page from left to right, the first signals applied to the charge electrode must result in deflections appropriate for the column of dots at the left edge of the character. As the print head moves, signals must be supplied at the proper moment for each succeeding column. Because the stream of drops cannot readily be turned on and off, where blank spaces are needed some drops must be discarded.

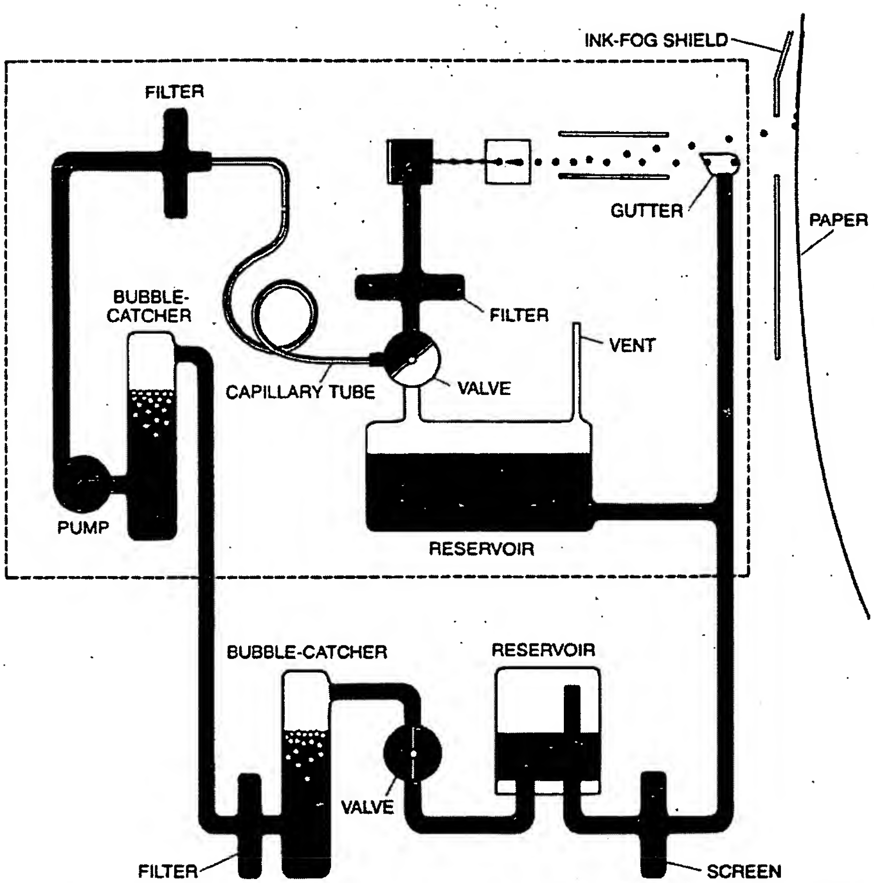
The trajectory of a drop can be calculated in a first approximation by assuming that the deflection is proportional to the voltage that appeared on the charge electrode at the time the drop formed. If the voltage is zero and the drop acquires no charge, its path will be unaffected by the electric field between the deflection plates. The drop will continue in a straight line. In the IBM 6640 and in other printers of similar design these undeflected drops are not allowed to reach the paper; instead they are collected in a gutter. Ink from the gutter is

returned to a reservoir and is ultimately recirculated to the print head. When a voltage is applied to the electrode, the drop acquires a charge and is deflected onto the paper. The greater the voltage, the greater the charge and the more sharply the drop is deflected.

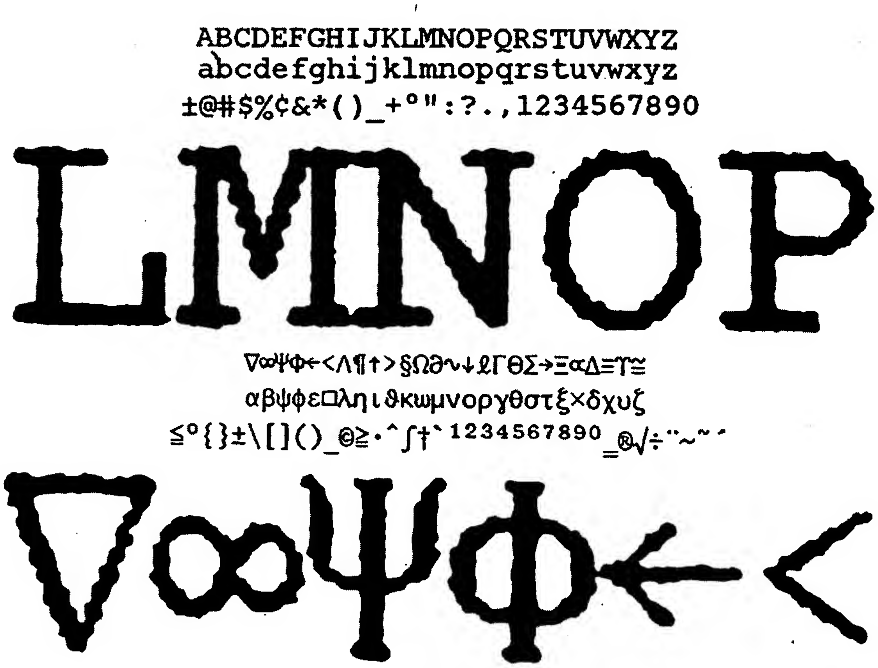
The idea of varying the charge on the drops and passing them through a constant deflection field, which was Sweet's innovation, may seem somewhat out of the ordinary. It may appear more natural to give every drop the same charge and to vary the voltage on the deflection plates. That is the method employed, for example, in the cathode-ray tube of an oscilloscope or a television receiver, where the deflected objects are not charged drops but individual electrons. The reason such a system would not work in an ink-jet printer can be understood by considering the forces acting on a drop or on an electron in the deflection field. A typical drop has a charge that corresponds to a million excess electrons, and the electrostatic force acting on the drop exceeds the force on a single electron by the same factor. The deflection induced by that force, however, depends not only on the charge but



MISPLACEMENT OF DROPS is caused mainly by aerodynamic and electrostatic disturbances while the drops are in flight. In a continuous stream of drops directed to the same point, such as the gutter, each drop moves in the wake of the preceding ones; all the drops are therefore subject to the same drag, which is less than that acting on a leading drop. If a single drop is deflected out of this stream (*a*), it is no longer sheltered by the preceding drops and so it slows down. Because the deflected drop spends a longer time in the field of the deflection plates, it is deflected through a larger angle and its trajectory takes it to a higher position on the paper than the intended trajectory. When two consecutive drops are deflected, the leading drop leaves a wake that allows the trailing drop to catch up. If the two drops are not highly charged (*b*), they can merge, so that a single oversize blob appears where two smaller dots were intended. If the two drops are highly charged (*c*), they approach each other and then scatter as a result of electrostatic repulsion, ultimately landing at unpredictable positions.



RECIRCULATION OF INK is necessary in an ink-jet printer because most drops never reach the paper but instead are collected in the gutter. The ink-handling circuit shown is that of the IBM 6640 document printer. Components within the broken-line rectangle are mounted on the moving print head. Several filters are included in the circuit in order to trap contaminants that might clog the nozzle. The jet must be started and stopped quickly to avoid dribbling ink on the charge electrode or the deflection plates; to that end the print head is equipped with a fast-acting valve that shunts excess ink to a reservoir. The components are not shown to scale.



SPECIMEN OF TYPE printed by the IBM 6640 is comparable in quality to that produced by a typewriter with a fabric ribbon. The type is shown at actual size above. In the enlarged characters below, the individual dots are clearly distinguishable, particularly in curves and diagonal lines, where the rectilinear array of deposited drops gives rise to a "stairstep" imperfection.

also on the mass. For the electron the ratio of charge to mass is 1.76×10^8 coulombs per gram, whereas for an ink drop it is about 10^{-6} coulomb per gram. Hence for a given field strength the deflection of a typical drop is smaller than the deflection of an electron by a factor of about 10^{14}.

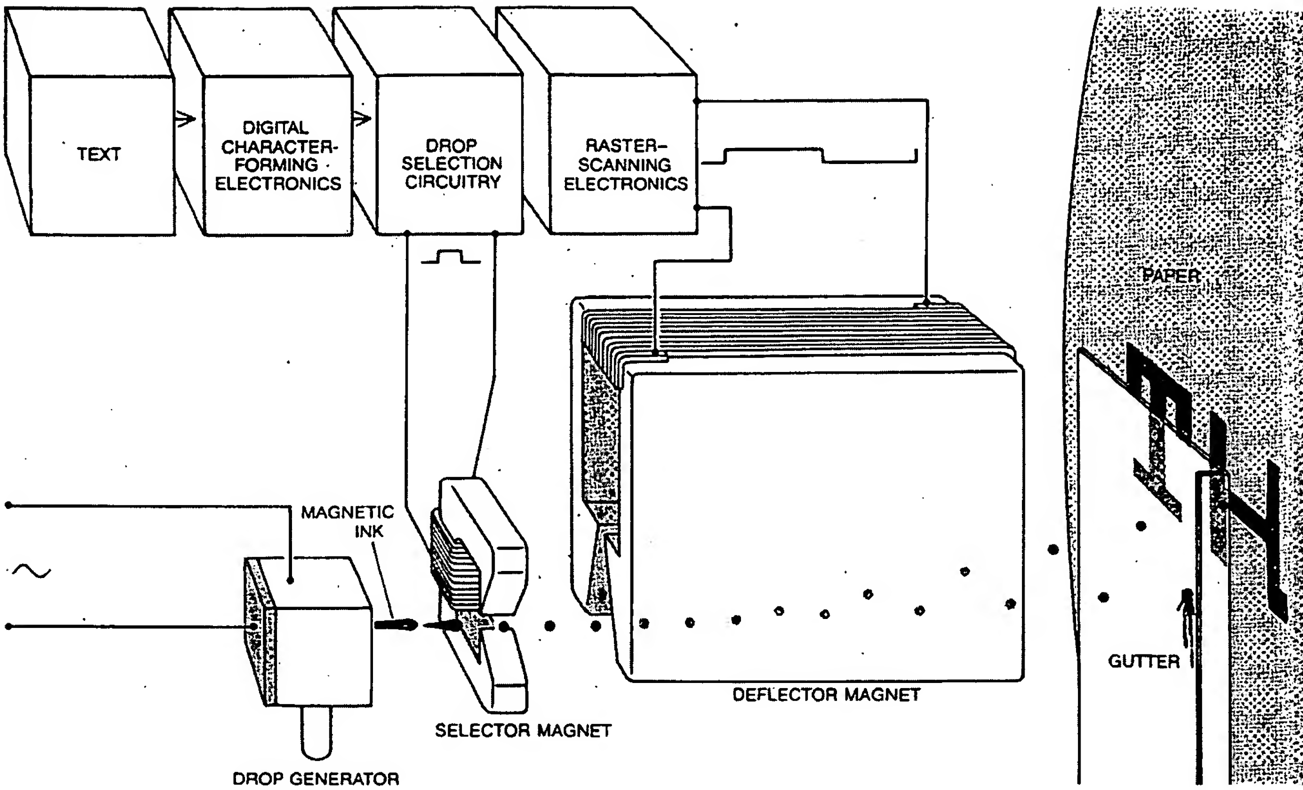
Because of the small ratio of charge to mass an ink drop is an extremely sluggish projectile and is difficult to steer. Characters of adequate size can be formed only by making the deflection plates as long as possible, so that each drop spends sufficient time under the influence of the deflecting field. The separation between drops is small, however, so that many drops are in the deflection field at the same time. It follows that if the drops were to be steered by altering the deflection voltage, their trajectories could not be determined independently.

The assumption made above that drop deflection is proportional to charging voltage is only an approximation, and in many instances it is not a very good one. Several factors can alter the trajectory of a drop. The most important ones are related to interactions between nearby drops.

One kind of disturbance takes place at the charge electrode, where the charge acquired by one drop can be influenced by the charges of the drops that precede it in the stream. The charge on a given drop is determined by the total electric field surrounding the drop. The major influence on this field is the positive voltage applied to the charge electrode, but any other charge in the vicinity will also exert an effect. In particular, if the preceding drop has a large negative charge, it will reduce the net positive voltage acting on the newly forming drop. As a result the charge carried away by the new drop will be smaller than what was intended. The corrective is to alter the applied voltage to compensate for the inductive interactions between nearby drops. Thus in order to calculate the correct charging voltage it is not enough to know where a drop is meant to strike the paper: the history of preceding drops must also be taken into account.

A more troublesome distortion of the printed character results from aerodynamic influences on the drop trajectory and from electrostatic repulsion between drops that carry a charge. These effects have proved to be important factors limiting the speed and resolution of ink-jet printing.

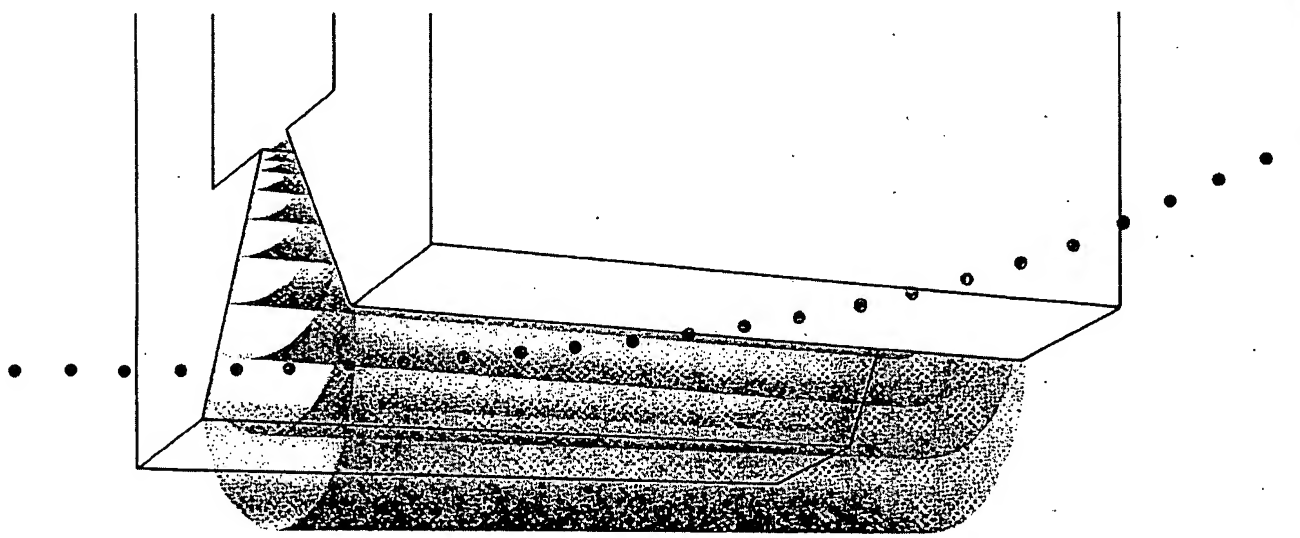
For a drop moving through still air aerodynamic drag is a force hundreds of times stronger than gravity and is comparable in magnitude to the electric forces created by the deflection field. When all the drops in a continuous stream are aimed at the same point (such as the gutter), each drop leaves



MAGNETIC INK-JET PRINT HEAD employs a ferromagnetic fluid as its ink. Drops of the ink can be steered in two dimensions by nonuniform magnetic fields, or field gradients. Vertical position is controlled by the field gradient of the deflector magnet; because this magnet is quite long several drops are under its influence at any given moment. Deflection in the horizontal plane serves merely to select which drops are allowed to reach the paper and which ones are intercepted by the knife-edge gutter. The selector magnet is short enough for it to affect only one drop at a time. As in an electrostatic printer, characters are formed by moving the print head across the page.

a wake that shelters the drops behind it and thereby reduces the drag acting on them. When a single drop is deflected out of the stream, however, it must make its own way through still air and is therefore slowed substantially. One result of this deceleration is that the drop spends a longer time in the deflection field than it would otherwise and reaches the paper above its intended position.

The distortion of the printed image can be more serious when two successive drops are deflected out of a continuous stream. The first drop in the pair feels the full effect of aerodynamic drag, but the wake it leaves shields the second drop and allows it to catch up with the first one. If the two drops are not highly charged (or to be precise if the product of their charges is not large), they may merge. As a result where two drops were meant to be placed in vertical alignment a single, larger blob appears at an intermediate position. If the two drops are highly charged, then as they approach each other electrostatic repulsion builds up. Instead of merging the drops bounce



MAGNETIC-FIELD GRADIENT is needed to deflect a drop of ferromagnetic fluid. In a uniform field (one with a gradient of zero) a drop would be subject to equal forces pulling in opposite directions. In a field gradient the drop is drawn toward the region of greater field strength. A nonuniform field can be generated by a magnet with beveled poles. The field is stronger where the poles are closer.

apart, landing at unpredictable positions often a considerable distance from the intended ones.

In principle it might be possible to compensate in part for these effects by adjusting the charging voltage, but the adjustment for any one drop depends in a complicated way on the trajectories of many other drops. Because the present theoretical understanding of the drop interactions is limited it has been necessary to rely on empirical methods. The commonest expedient is to leave uncharged "guard" drops, which go into the gutter, between pairs of drops that are charged and deflected. By throwing away at least half of the available drops this technique reduces misregistration, but it also reduces printing speed.

There is much more to building a workable ink-jet printer than the physics of drop generation and placement. For example, the formulation of the ink is not a trivial exercise. The ink must be electrically conductive; it must also be free of particulate matter, since that might clog the nozzle. As a result of evaporation and temperature fluctuations the properties of the ink change, which makes necessary periodic adjustments to the ink pressure and to the timing of electronic events. In the IBM 6640 these adjustments are made automatically by a system that senses both the aimpoint of the jet and the instant of drop formation. Whenever the jet is started or stopped, there is a risk that a dribbling or drooping jet will contaminate the electrodes of the print head, a risk that is minimized by a fast-acting valve. A particularly difficult requirement is that the ink, the ink-supply system and the nozzle not interact chemically. Engineering considerations of this kind are the dominant factors in the design of a machine that must operate reliably in commercial service.

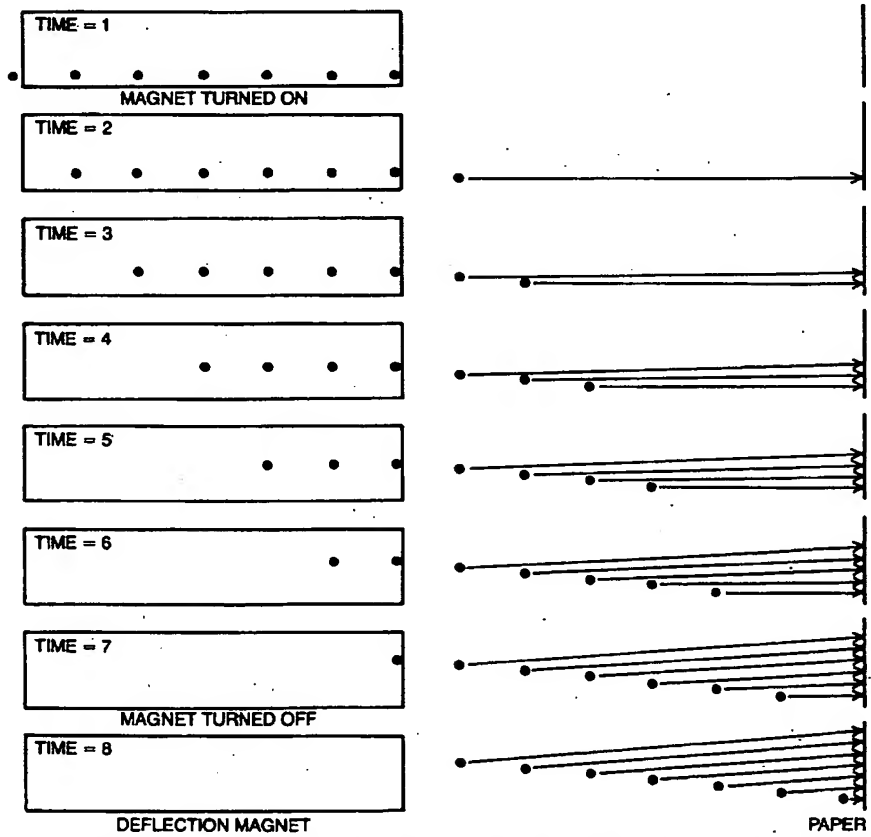
An alternative ink-jet technology that might avoid some of the complexities of the electrostatic device is a magnetic drop-deflection system devised by George J. Fan and Richard A. Toupin, who work in our laboratory at the IBM Thomas J. Watson Research Center at Yorktown Heights, N.Y. An essential component of the system is a magnetic ink, one of a class of liquids called ferrofluids developed in the 1960's by workers at the Avco Corporation. Such a fluid is a suspension of minute particles of magnetite, the magnetically active form of iron oxide. The fluid cannot retain a permanent magnetization, but it is strongly attracted by a magnet.

A moving drop of ferrofluid ink can be deflected by passing it through a magnetic-field gradient. The path of the drop would be unaffected by a uniform field, but in a nonuniform one the drop is drawn toward the region of greater field strength. It is an easy matter to create such a field gradient; in a *C*-shaped magnet with beveled pole pieces, for example, the field is stronger where the poles are closer together.

A magnetic ink-jet printer employs a synchronized drop generator much like the one in an electrostatic printer, but the generator usually operates at about half the drop frequency. The apparatus for deflecting the drops and forming characters is quite different from the corresponding electrostatic devices. For a given field gradient deflection is proportional to the net magnetic moment of the drop, which cannot be controlled independently from drop to drop; the magnetic moment per unit volume of fluid is a fixed property of the ink. For this reason drops cannot be individually selected for deflection. One alternative to the aiming of individual drops is to create a raster of drop positions, much like the pattern of electron scan lines in a television picture, and to provide a means for "blanking" selected positions.

Suppose the drops pass through a field gradient created by an electromagnet whose pole pieces are exactly seven drop periods long. The gradient is arranged so that drops exposed to the field will be deflected upward before proceeding to the paper. If the field is turned on just as a drop is leaving the influence of the magnet, the drop will continue on its original trajectory unaffected by the field. The next drop will have been exposed to the field gradient for one drop period before it leaves the magnet, and so it will be deflected through a small angle. The next drop will have been exposed to the gradient twice as long, and so it will be deflected twice as much. The deflection increases uniformly for each succeeding drop through the eighth one; for the eighth drop the field is on the entire time the drop is between the pole pieces, and so its deflection is the maximum possible.

On the printed page this sequence of eight drops creates a vertical line made up of eight uniformly spaced spots; by moving the print head across the page horizontally the pattern can be repeated



RASTER OF DROPS is created by the magnetic deflection system. Here the length of the deflection magnet is assumed to be six times the drop spacing and the magnet is actuated cyclically, so that it spends seven drop periods on followed by seven periods off. When the magnet is turned on (*1*), the drop just emerging from between the poles is unaffected by the field gradient and proceeds directly to the paper. When the next drop emerges (*2*), it has spent one drop period under the influence of the field gradient, and so it receives a small deflection. The next drop (*3*) spends two periods in the field, and so it is deflected twice as much. With each succeeding drop through the seventh one the deflection grows by the same increment; for the seventh drop the field is turned on the entire time the drop is between the pole pieces, so that no greater deflection is possible. The result of the progressively increasing deflection is a vertical column of dots on the paper. In order for the column to form a character selected drops are deleted by diverting them into a gutter that would lie outside the plane of the illustration.

indefinitely. All that is needed in order to create characters is a means of selectively discarding some of the drops. The drops at positions to be left blank must be intercepted before they reach the paper; so must the six drops that follow each upward vertical scan. The reason for catching the six trailing drops is that when the magnet is turned off after the eighth drop, the deflection does not immediately return to zero. When the field is removed, it has already influenced the ninth drop for six drop periods, the 10th drop for five periods and so on. Drops eight through 14 are therefore discarded and a new scan begins with drop 15.

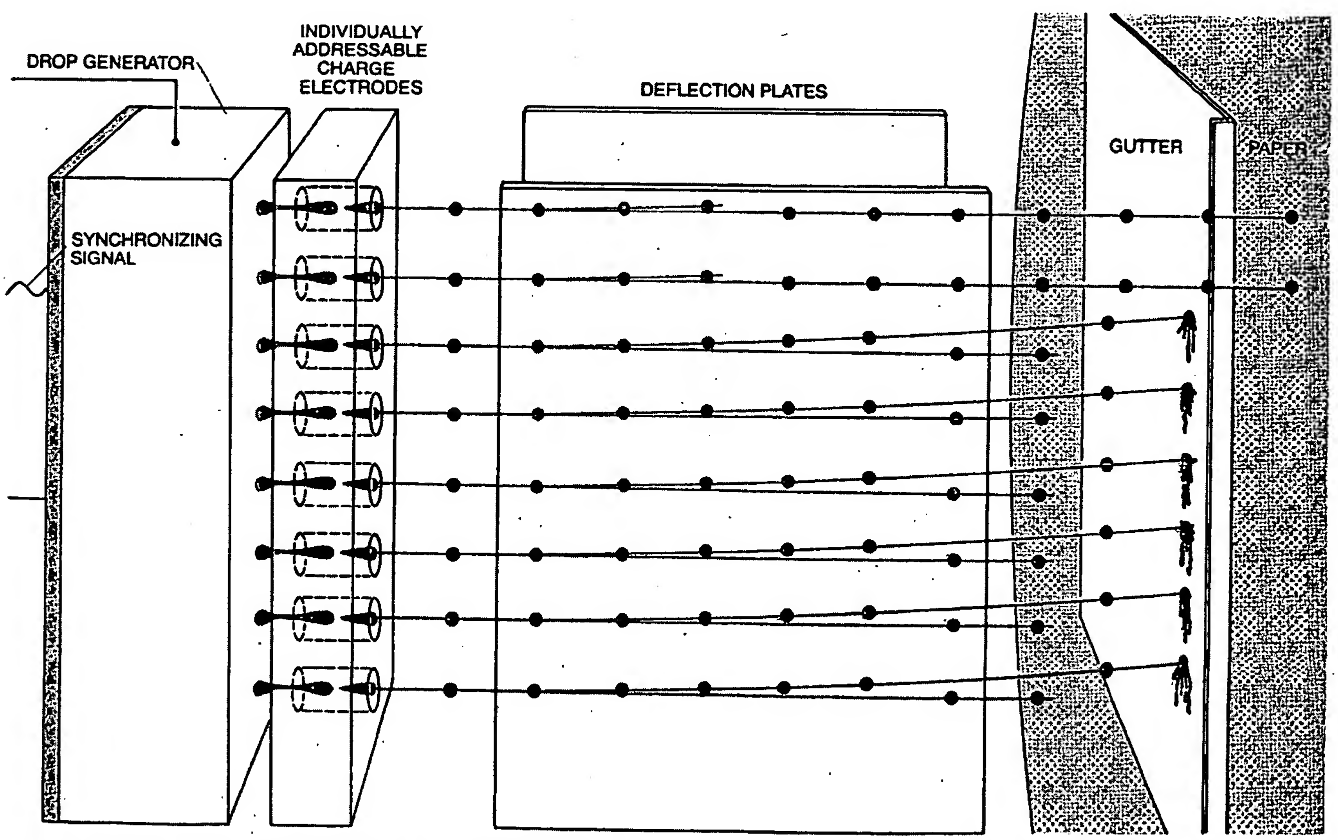
The means for eliminating selected drops from the sequence is another magnetic deflector. Since individual drops are to be selected, the length of the pole pieces must be shorter, less than one drop period, but that is acceptable because little deflection is needed. The small selector magnet is oriented at right angles to the deflection magnet so that the drops it designates are pulled out of the plane of the raster scan. The selector is positioned upstream of the deflector magnet, and so the drops it influences still pass through the deflecting gradient; before they reach the paper, however, they are intercepted by a knife-edge gutter and recirculated. The drops that remain in the plane of the raster pass the gutter and go on to the paper.

An important feature of the magnetic printer is that the maximum possible deflection is essentially independent of drop size. In an electrostatic printer a larger drop has more mass but can accommodate little additional charge, so that it is deflected less. The force acting on a magnetic drop, on the other hand, is proportional to the drop's mass since a larger drop has more magnetite in it. For this reason a magnetic ink-jet printer might operate efficiently with the large drops needed for a low-resolution matrix printer.

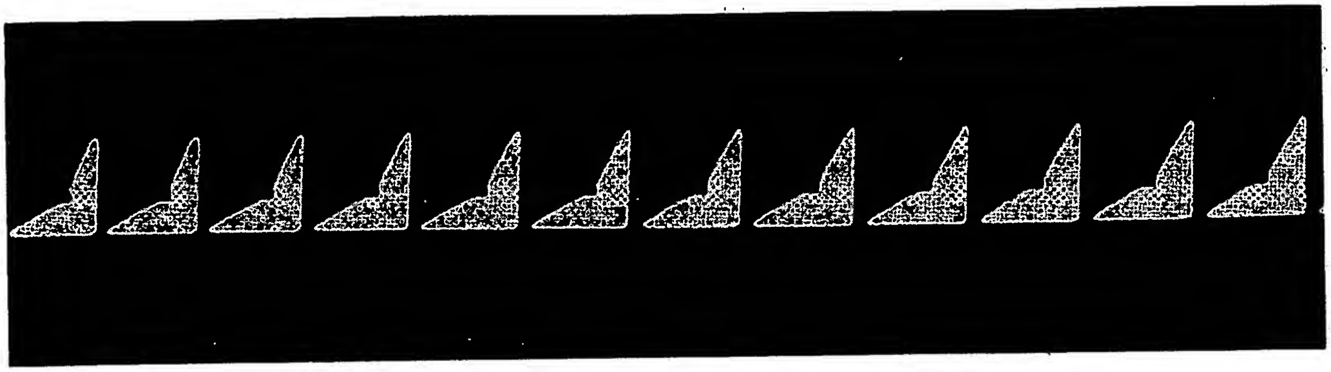
Another capability of the magnetic printer is the deflection of each drop in two dimensions. A printer with two axes of deflection could form characters not by selecting dots from a fixed array but by drawing curves and line segments. Fan and his co-workers have demonstrated a magnetic printer that draws characters in this way.

In an effort to improve the speed of the ink-jet process we have also investigated printers in which an array of nozzles operate in parallel, another configuration foreseen by Sweet. The technology employs electrostatic deflection; it has been called binary printing or nozzle-per-spot printing. The print head consists of many closely spaced nozzles supplied with ink from a common manifold and synchronized by a single piezoelectric element. The jet from each nozzle passes through a charge electrode that can be individually addressed; then the drops from all the jets pass between a common pair of deflection plates. Each charge electrode has only two possible states; it is either on or off. If a drop is charged, it is deflected into a gutter and the ink is recirculated; otherwise the drop passes undeflected to the paper. It is because a drop has only these two possible destinations that the printing is called binary.

The Mead Corporation has built a high-speed printer on these principles. Some 600 nozzles are lined up across the width of the page (about five inches) and the paper is continuously drawn under them. Each charge electrode is turned on and off in the proper sequence to form an entire line of dots. The device is capable of printing up to 45,000 lines per minute but has comparatively low



BINARY PRINT HEAD employs multiple ink jets and steers each drop to one of only two possible destinations. If a drop is uncharged, it proceeds straight to the paper; if the drop is given a charge, it is deflected into the gutter. The nozzles are arranged in a vertical column and share a single pressure manifold and synchronizing signal. Each ink stream, however, is provided with a separate charge electrode, so that drops can be selected individually for printing or for deletion. All the drops pass through a common pair of deflection plates, where drops that have been labeled with an electric charge are pulled into the knife-edge gutter. Because the printing is done with uncharged drops most electrostatic interactions between drops in flight are eliminated. Moreover, because only small deflections are needed voltages applied to the electrodes can be reduced and so can the distance between nozzles and paper, thereby minimizing aerodynamic effects.



ROW OF NOZZLES for a binary print head was etched in silicon by techniques similar to those employed in making microelectronic devices. In this scanning electron micrograph the nozzles are seen from the ink-manifold side. The shape of the nozzles is determined by the orientation of the planes of atoms in the single-crystal wafer of silicon and for that reason can be precisely controlled. Each nozzle has the form of a truncated pyramid; the ink issues from the smaller base. The square shape of the aperture has no effect on the drop stream.

resolution. So far it has been employed mainly for the printing of "computer letters": mailed advertisements that include names or other information that is different in each copy.

At IBM Research we have investigated the design of a nozzle-per-spot printer in which a moving print head would reproduce characters serially at high resolution. Such a binary printer offers a number of advantages over the analogue electrostatic printer described above. The drops from a binary array of nozzles are less affected by electrostatic and aerodynamic interactions, so that drop placement is more easily controlled. The circuitry needed for drop control is also greatly simplified. On the other hand, the fabrication of the nozzles and the charge electrodes becomes a formidable challenge.

The replacement of analogue devices by binary ones is a well-established trend in the electronics industry as a whole, made possible by the discovery that even very complex circuitry can be manufactured cheaply when it is represented as a pattern on the surface of a wafer sawn from a single crystal of silicon. We and our associates adopted the same techniques for the fabrication of the essential components of the binary print head.

The fabrication of the nozzle array demands great precision. In a typical array some 40 nozzles, each from 20 to 40 micrometers in diameter, must be packed together in a line whose length is roughly equal to the height of a typewriter character. The spacing of the nozzles must be uniform; what is more important, the jets issuing from them must be parallel to within high accuracy. For example, if the paper is only one centimeter from the nozzle, a deviation from parallel alignment of less than .1 degree would result in a drop misplacement of about 20 micrometers, which is roughly the maximum error that can be tolerated in high-quality printing. Uniform velocity is as important as uniform direction, and it is harder to achieve. If the drops do not have equal transit times between the nozzle and the page, then the motion of the print head with respect to the paper gives rise to errors in drop placement.

Several approaches to nozzle fabrication have been investigated, including drilling holes with laser light or an electron beam and assembling a bundle of fine glass capillaries. The nozzle for the IBM 6640 is made by mechanical drilling. For the binary array we formed the nozzles by chemically etching holes through a silicon wafer, a method that had been proposed in a somewhat different form by Charles Chiou and his collaborators at the IBM Laboratory in San Jose, Calif. Many copies of the pattern to be etched can be defined on a single wafer by photolithography. The etching itself can then be carried out in batches of several wafers each. In a final step the wafers are cut into chips, each chip bearing a nozzle array. Silicon was chosen not because of any intrinsic property that makes it a particularly suitable material for the nozzles but because there is a highly developed technology for the fabrication of precise microscopic structures out of silicon.

An etched nozzle has the form of a truncated pyramid, the large base forming the nozzle entrance on one side of the wafer and the smaller base the exit. The sides of the pyramid are defined by planes of atoms in the crystal, and hence their orientation is in principle fixed to within a few atomic diameters. For protection against corrosion a thin film is applied to the array, such as a layer of silicon dioxide.

The jet emerges from the nozzle with a square cross section but quickly relaxes to a circular one. At the outset it was not known what effect the square orifice might have on the formation of the drop stream, but the shape turned out to be unimportant. The corners of the square, having high curvature, are immediately flattened by surface tension. Because of inertia there is some overshoot, so that each corner of the square develops into a concavity, but the ensuing oscillation is damped too quickly for it to influence drop formation. For the purposes of the printer the jet from a square nozzle is virtually identical with one from a round nozzle.

Arrays of as many as 40 nozzles have been fabricated and tested. The jets have excellent directional characteristics, which can be attributed to the crystal structure of the silicon, which determines the shape and orientation of the nozzles. The sharp edge of the opening also contributes to uniformity by creating a stable point of detachment for the fluid. The closely matched velocities of the jets are an indication that all the nozzles are the same size.

The fabrication of the charge electrodes also presents considerable difficulties. The reason is that each electrode in the array must be electrically isolated so that it can be turned on and off independently of all the other electrodes. Moreover, attaching a separate wire to each electrode and connecting it to a distant electronics module could be awkward. One of us (Kuhn) therefore suggested that the array of charge electrodes also be made in a single chip of silicon. Integrated circuits could be created on the same chip as the electrodes themselves and during the same processing steps. Signals intended for the various electrodes could then be sent over a single wire in encoded form. An on-chip circuit would decode the signals and distribute them to the proper destinations.

The pyramidal holes employed as nozzles are not suitable for charge electrodes, but holes of other shapes can be created by etching silicon with a different crystallographic orientation. We chose to etch long slots with the long walls parallel. The holes were etched in thick wafers of silicon that had been doped with an electron-donor impurity, converting the material into an *n*-type semiconductor, which has an excess of electrons. The walls of each slot were then treated with another dopant to make them *p*-type semiconductors, which have a shortage of electrons or an

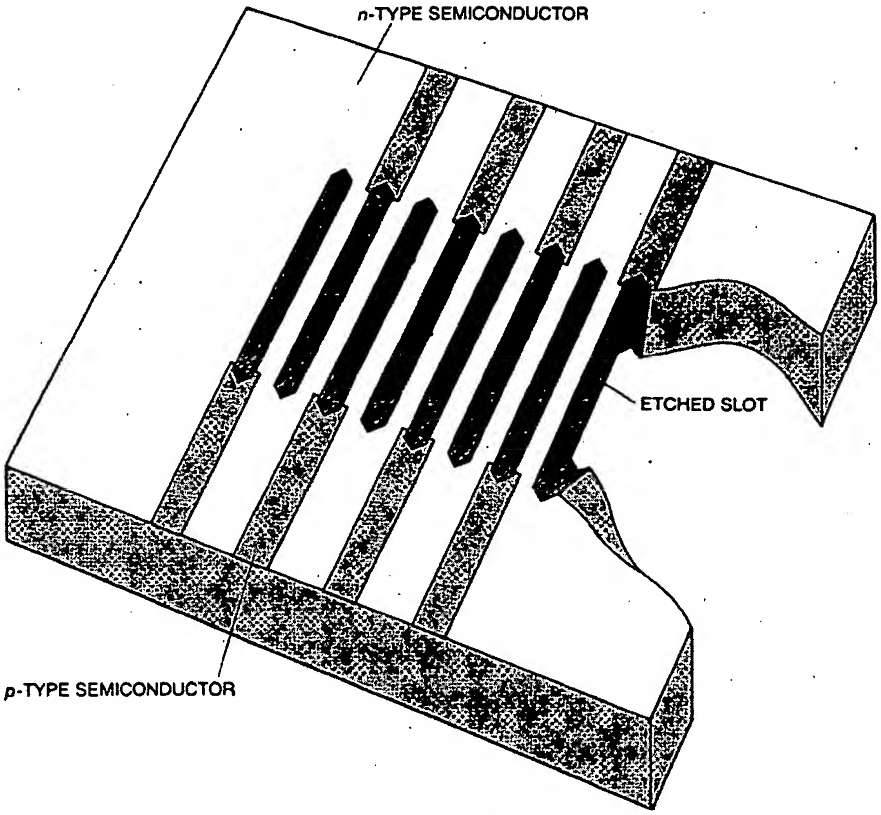
excess of "holes." The junction between the n-type and p-type layers represents a diode; when an appropriate voltage is applied across the junction, each slot is electrically isolated from its neighbors. In addition the p-type surface serves as a conducting layer for the electrode.

A print head can be assembled from these components by mounting the nozzle array on a manifold with a piezoelectric driver to provide the synchronization signal. The charge-electrode array is then bonded to a printed-circuit board, which holds the array in proper alignment with the nozzles and also carries the drive signals to the electrodes. Rudimentary printing experiments have been carried out with such prototype assemblies. Both the nozzles and the charge electrodes are spaced on centers .3 millimeter apart. The jet diameter is about 25 micrometers, and the jet velocity is about 12.5 meters per second.

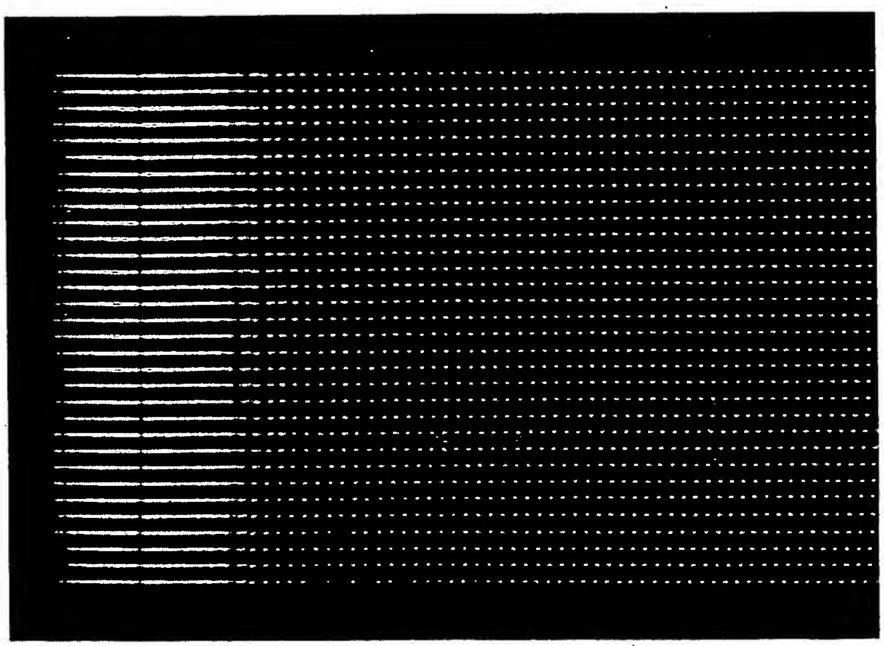
It may well be possible to extend silicon fabrication methods to still another component of the binary print head. Synchronization of the drop stream by an electromechanical transducer such as a piezoelectric crystal is unsatisfactory for very long arrays of nozzles because distant nozzles may not receive the same mechanical excitation. The problem can be avoided by direct, nonmechanical synchronization of the stream with an electrical signal. If an oscillating voltage is presented on an electrode near the emerging jet, a mirror image of the electrode's charge is induced in the fluid jet, which is therefore attracted to the electrode. The result is a periodic deformation in the surface of the jet, which is precisely the kind of signal needed for synchronized drop formation.

One way to provide such a synchronizing signal is by fabricating an electrode for each nozzle in the silicon substrate of the nozzle array. Synchronization has been demonstrated with such nozzle arrays, but in our experiments it was not strong enough for reliable printing. The limiting factor is the electrical strength of the insulating oxide layer on the surface of the nozzle chip, which limits the voltage that can be applied to the synchronizing electrode. With an improvement in coating technology the all-electronic ink-jet print head should become possible.

There is a satisfying symmetry in the development of all-electronic printing. It was the proliferation of computers in the past 15 years, and more recently of microelectronic devices, that created the need for machines that quickly and legibly print a document on demand. Electronic technology is essential to all such printers, including even the electromechanical ones, and it is the very basis of the ink-jet mechanism. With the adoption of semiconductor processing methods for the fabrication of the printing machinery the cycle has fully closed.



ARRAY OF CHARGE ELECTRODES was also etched in silicon, but in material with a different crystallographic orientation. As a result the holes have a different shape: they are slots instead of pyramids. Because each stream of drops must be steered independently of the other streams, each charge electrode must be electrically isolated. That is accomplished by treating the walls of the slots to make them p-type semiconductors, whereas the bulk material is an n-type semiconductor. When a bias voltage is applied, each slot acts as a diode and no current can flow from one electrode to another. Ultimately it should be possible to fabricate an integrated circuit on the surface of the chip for the purpose of decoding signals to the electrodes.



MULTIPLE STREAMS OF INK DROPS emerge from an etched-silicon nozzle array. The image is greatly magnified, the actual size of the array being roughly the height of a typewriter character. The streams of drops exhibit several properties that are important in a binary, or nozzle-per-spot, printer. The drops are uniform in size and spacing, and the streams are parallel to within high accuracy. The velocity of the drops is also nearly uniform, the only significant distortion being a tendency for drops at the periphery to move slower than those at the center.

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